EXPERIMENTAL EVALUATION OF INFLUENCE OF TOTAL DIRECTIONAL TRANSMITTANCE OF DIFFERENT SAMPLES OF GLASS ON FLAT SOLAR COLLECTOR THERMAL EFFICIENCY

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Abstract. *The actual study deals with of experimental determination of the total directional transmittance (τ) of different samples of glass and their influence on thermal efficiency (η) at a solar collector, evaluated by their respective correction factor (κ). For the determination of total directional transmittances under real operation conditions comparative tests were performed between the incident solar radiation and radiation transmitted by each sample. The experiments to evaluate the instantaneous thermal efficiency of solar collector for each sample, according to the ANSI standard ASHRAE 93-2003, were made in a solar simulator. To determine the K factor and the monthly production of specific energy was used the same statistical treatment as defined by ANSI ASHRAE and applied in the Brazilian Labeling Program (PBE/INMETRO). A type of flat glass was used as the control sample in all experimental stages.*

***Keywords**: Total Directional Transmittance; Thermal Efficiency; Factor Correction of Angle of Incidence of Solar Irradiation; Solar Collector*

1. INTRODUCTION

Nowadays, there is in the Brazilian market of solar collectors a constant concern of businesses in obtaining the best relationship between cost and thermal efficiency of their products. To this end, are evaluated a variety of materials and design parameters, including the transparent cover, scope of this study.

Knowledge of total directional transmittance of the glass to be used in the manufacture of flat solar collectors, allows a better design of solar thermal facilities, and enables the creation of different product lines, according to market requirements thus, the objective of this work, requested by one Brazilian glass manufactory named “União Brasileira de Vidros (UBV)”, has been conducting trials in 6 different samples of glass (Sample 1 - Style, Sample 2 - Mini Boreal , Sample 3 - Mini Boreal Chinês, Sample 4 - Pirâmide, Sample 5 - Anti-Reflexo and Sample 6 (Float-Control[1]) to assess their total directional transmittances *(τ)*. Moreover, tests were also conducted indoors by a continuous solar simulator to evaluate the influence of each sample in the thermal efficiency *(η)* of a flat solar collector.

2. LITERATURE REVIEW

For engineering purposes, it is often desirable to tailor the radiative properties of surfaces to increase or decrease their natural ability to absorb, emit, or reflect radiant energy. This can be done to provide a desired spectral or directional performance.

For surfaces used in colletion of radiant energy like a solar collectors it is desirable to maximize the energy absorbed by a surface while minimizing the loss by emission such surfaces are called “spectrally selective”. This

[1] Float Glass (Control Group): Smooth Glass, 3 mm, normally used in solar collectors on the market.

surfaces can highly their performance of a solar collector. It is also important to point out the selective transmission absorption behavior of a glass as nonopaque material. Figure 1 shows the overall spectral transmittance of glass plates for normally incident radiation.

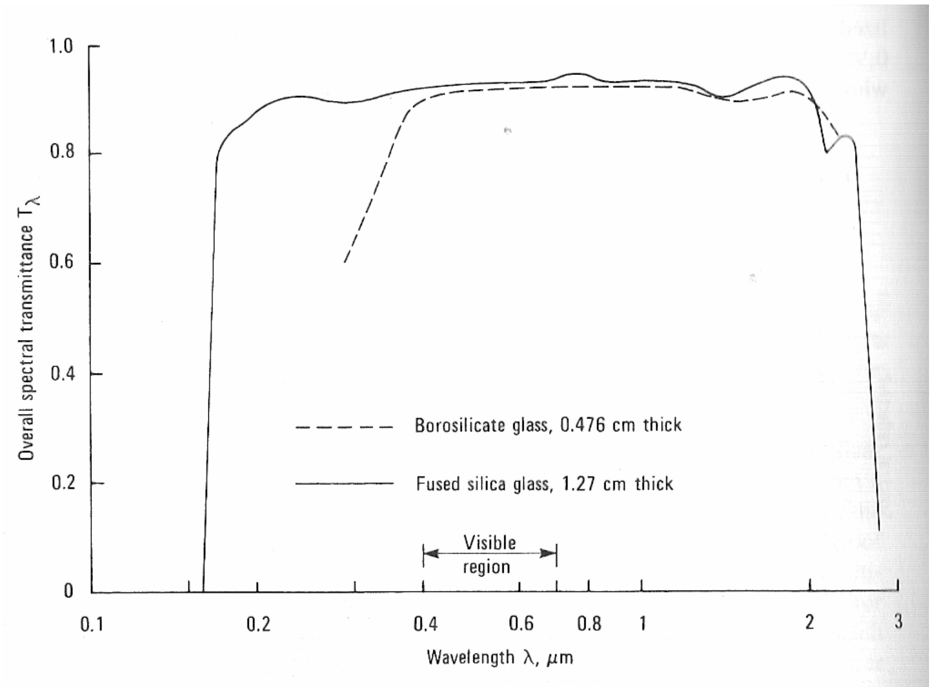


Figure 1. Normal overall spectral transmittance of glass (includes surfaces refletions) at 298 K (scanned from Siegel & Howell (1992)).

It is also know that the overall transmittance includes the effect of absorption within the glass and multiple surface reflections; it is given by the equation 1 according to Siegel & Howell (1992).

$$T_{\lambda} = T_{\lambda} (1-\rho_{\lambda})^2/(1-\rho_{\lambda}^2 T_{\lambda}^2) \quad (1)$$

where $T_{\lambda} = \exp(-a_{\lambda} d)$ and $\rho_{\lambda} =[(n-1) / (n+ 1)]^2)$

a: absorption coefficient;
T: ratio of energy transmitted through plane system ti energy incident (overall transmittance);absolute temperature;
λ : spectrally dependent;
ρ: Stefan Boltzmann constant;
n: simple index of refraction;

For small values of $(-a_{\lambda} d)$ equation 1 reduces to:

$$T_{\lambda} = (1-\rho_{\lambda}) / (1+\rho_{\lambda}) \quad (2)$$

For a glass n is equal to 1.5 so $\rho_{\lambda} = 0.04$ then only including one reflection losses gives as $T_{\lambda} = 0.92$. In figure 1 the fused silica has very low absortion in the range $\lambda = 0.2$ to 2 µm, and $T_{\lambda} = 0.9$ in this region as a result of surface reflections. Ordinary glasses typically have two strong cutoff wavelengths beyond wich the glass becomes highly absorbing and T_{λ} decreases rapidly to near zero except for very thin plates. The measures curve for fused silica in figure 1 shows this clearly. There are strong cutoffs in the far ultraviolent at $\lambda = 2.5$ µm. The glass will therefore be a strong absorver or emitter for $\lambda = < 0.17$ µm and $\lambda > 2.5$ µm. Figure 2 shows the overall transmittance for various thicknesses of soda-lime glass, wich is more absorving than fuse silica. The effect of absorting is illustrated quite well as the thickness increases.

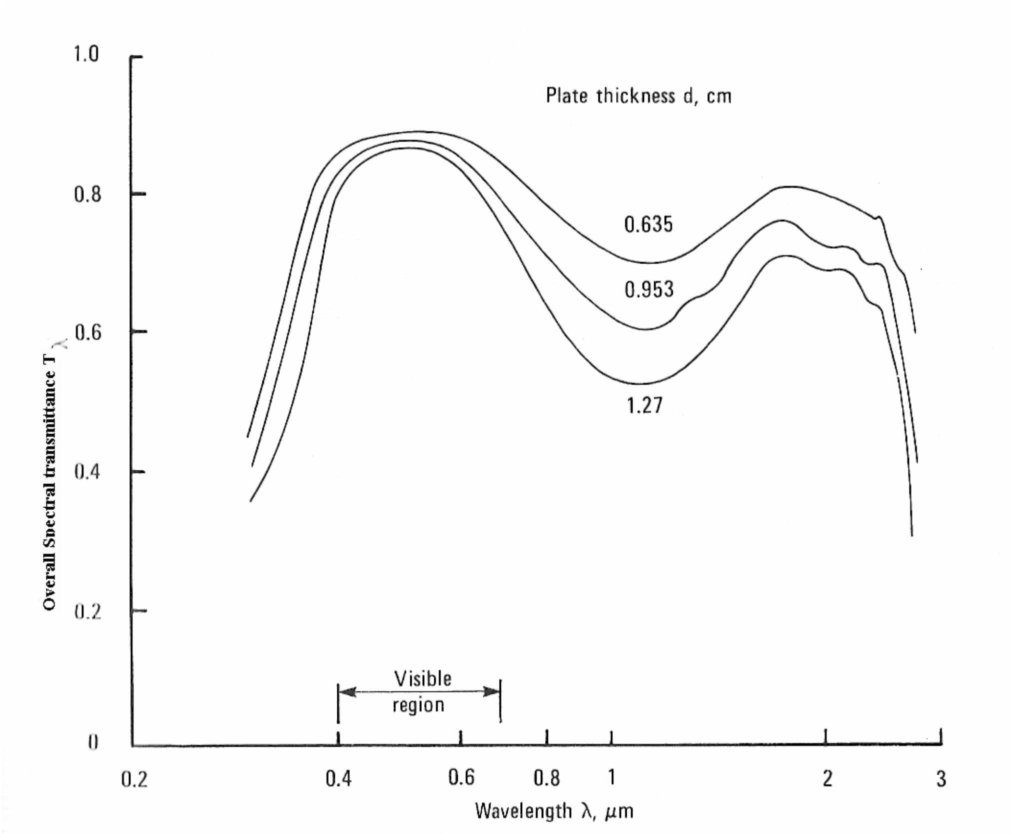


Figure 2. Effect of plate thickness on normal overall spectral transmittance of soda-lime glass (includes surface refletions) at 298 K (scanned from Siegel & Howell (1992)).

The total transmittance *(τ)* is defined as the fraction of incident solar radiation that is transmitted by the transparent integrated over coverage for all wavelengths and the enclosing hemisphere. Value contributes significantly in determining the instantaneous thermal efficiency of solar collectors *(η)*, namely:

Where:

$$\eta = \frac{A_{TSP}}{A_{EXT}} \left\{ F_R \left(\tau_c \alpha_p \right) - \frac{F_R U_L \left(T_{fi} - T_{amb} \right)}{G} \right\} \qquad (3)$$

A_{EXT}: external area of the solar collector, in m^2;
A_{TSP}: the coverage area, in m^2;
F_R: factor of removing heat from the solar collector;
τ_c: transmittance of the cover;
α_p: absorptivity of the plate;
U_L: overall coefficient of heat losses;
T_{fi}: temperature of the fluid into the solar collector;
T_{amb}: Ambient temperature;
G: global solar irradiance incident on solar collector plan.

In experimental testing, in accordance with the procedures required by the test standard ANSI ASHRAE 93-2003 and used by the Brazilian Label Program of Solar Collectors (PBE), the angle of incidence of direct solar radiation (θ) should be lower to 30º. As the daily operations of solar thermal facilities includes angles of incidence greater than the value defined by the standard, this study aims to evaluate the transmittance of transparent roof and its impact on efficiency and daily energy production in such conditions thus, for calculation of solar angles a subroutine namely SOLPLAN was developed based on classical models, available in Duffie and Beckman (1991). The input data to be provided are: latitude location, day and month of the year and inclination of the bench test. The routine calculated the solar time, hour angle, incidence angle of direct solar radiation at intervals of 15 minutes.

To determine the daily production of energy, the correction factor is introduced $K_{\tau\alpha}$ in equation 1 as:

$$\eta = \frac{A_{TSP}}{A_{EXT}}\left\{ K_{\tau\alpha}\left[F_R(\tau\alpha)_n\right] - F_R\,U_L\left(\frac{T_{fi} - T_{amb}}{G}\right)\right\} \tag{4}$$

where $K_{\tau\alpha}$ is defined by the ratio between the thermal efficiency measure for a given angle of incidence and the maximum value obtained in normal incidence for a difference between the temperature of the water entering the collector and the ambient temperature is less than 1K. According to the procedure of ANSI ASHRAE 93-2003 (RA91), its dependence on the angle of incidence should is expressed as:

$$K_{\tau\alpha} = \mathbf{a} + \mathbf{b}\left(\frac{\mathbf{1}}{\mathbf{cos}\ \theta} - 1\right) \tag{5}$$

Where the parameters a e b are experimentally determined.

The energy produced by solar collector for an hour, is equivalent to the product of its thermal efficiency for the incident energy into the collector in the same period. The time value is multiplied by 30 to obtain the energy generated during a month, each time interval. The sum of hourly values for the "i" times of day, with satisfactory level of sunlight, provides a monthly production of energy. Thus, we have:

$$E_{MON} = \frac{30}{1000}\sum_{i=1}^{9}\eta\, G A_{ext} \quad [\text{kWh/month}] \tag{6}$$

The constant 1000 is only to convert the unit in kWh /month, thus allowing a better assessment on the part of consumers, energy savings to be obtained using the solar collector.

The transmission behaviour show in figures 1 and 2 provides glass windows with important ability to trap solar energy. This means that glass has low absorptance for solar radiation; consequently solar radiation passes readily through a glass window. The emission from a objects at ambient temperature inside the enclosure is at long wave legths and is trapped because of the high absorptance (poor transmission) of the glass in the long wavelength spectral region. This trapping behaviour us called “greenhouse effect” according to Siegel & Howell (1992).

3. METHODOLOGY AND EXPERIMENTAL PROCEDURE

The experimental methodology was developed based on the comparison of instantaneous values of incident solar radiation (W/m²) obtained by two accuracy pyranometers (Eppley- Model PSP) properly calibrated[2] and installed in an external test bench, as shown in Figure 3a. The pyranometer 1 was installed above the glass, and pyranometer 2, under the transparent roof in evaluation, see Figure 3b.

(a) (b)

Figure 3.(a) External test bench (b) pyranometers 1 and 2 installed on the bench.

The glasses studied, Figure 4, and their thicknesses were identified and they are: Sample 1 (3 mm) Sample 2 (3 mm), Sample 3 (3 mm), Sample 4 (3.5 mm), Sample 5 (2.2 mm) and Float (flat 3 mm). The samples had surface area of about 1m².

[2] Pyranometer 1 with constant calibration: 8.37 microvolts/W/m²
Pyranometer 2 with constant calibration: 9.30 microvolts/W/m²

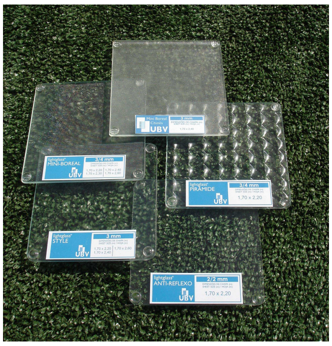


Figure 4. Identification of samples

For the acquisition and oversight of the data, we used an Agilent 34970A datalogger (Figure 5a) and the software LabView®/National Instruments® (Figure 5b). Data were collected at intervals of 30 seconds.

(a) **(b)**

Figure 5. (a) datalogger / (b) screen supervisor

It is important that the tests required to establish a daily routine which included the cleaning and inspection of samples in test, calculation of slope and recommended correct positioning of the bench. The daily average for data collection was from 8:00 am to 5:00 pm.

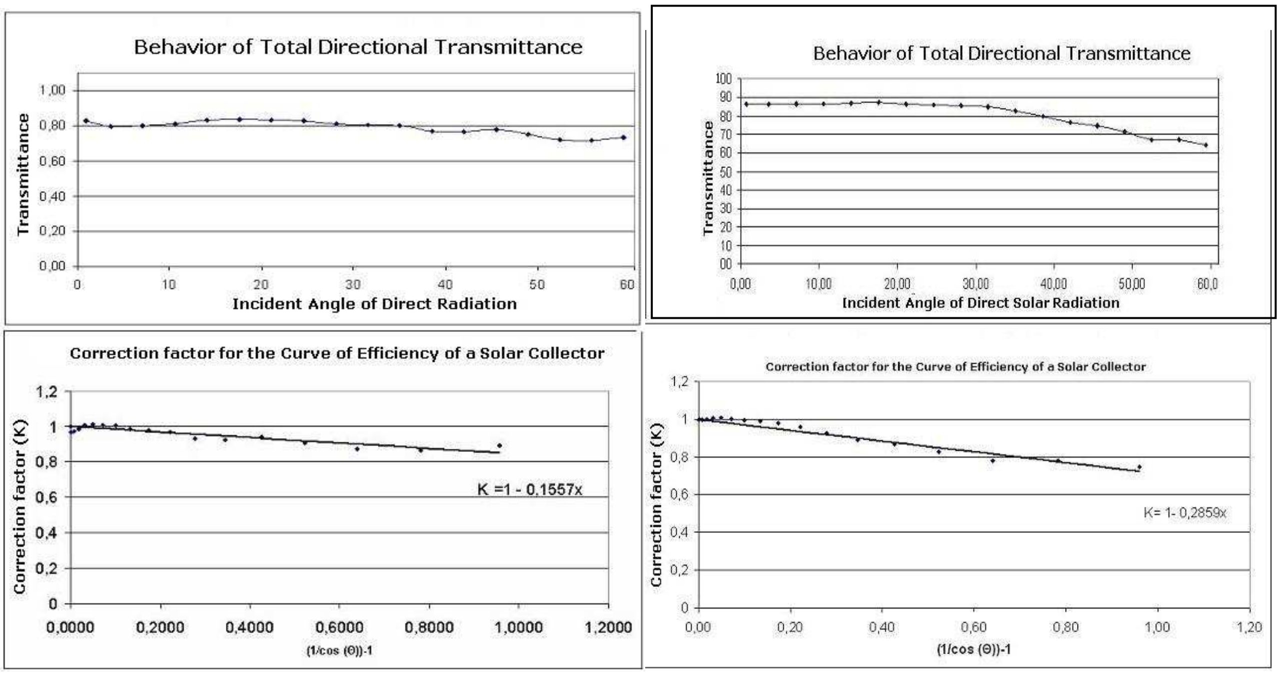
After statistical processing of data was calculated the total transmittance of the transparent covers for each angle of incidence of the direct component of solar radiation in the range from 0º to 60º. Finally, it was determined experimental linear equation of the correction factor $K_{\tau\alpha}$ for each sample according to ANSI / ASHRAE 93-2003 - Methods of Testing to Determine the Thermal Performance of Solar Collectors. The next step was to conduct experimental testing of instantaneous thermal efficiency, according to ANSI / ASHRAE 93-2003, for each sample in a continuous solar simulator testing procedure in according with Figure 6.

Figure 6. Samples in the test of thermal efficiency in solar simulator.

4. EXPERIMENTAL RESULTS

The results are summarized as graphs and tables provided below and the concomitant discussion of these results will be present in futher items. Below are the results of external and indoor tests for each sample of glass.

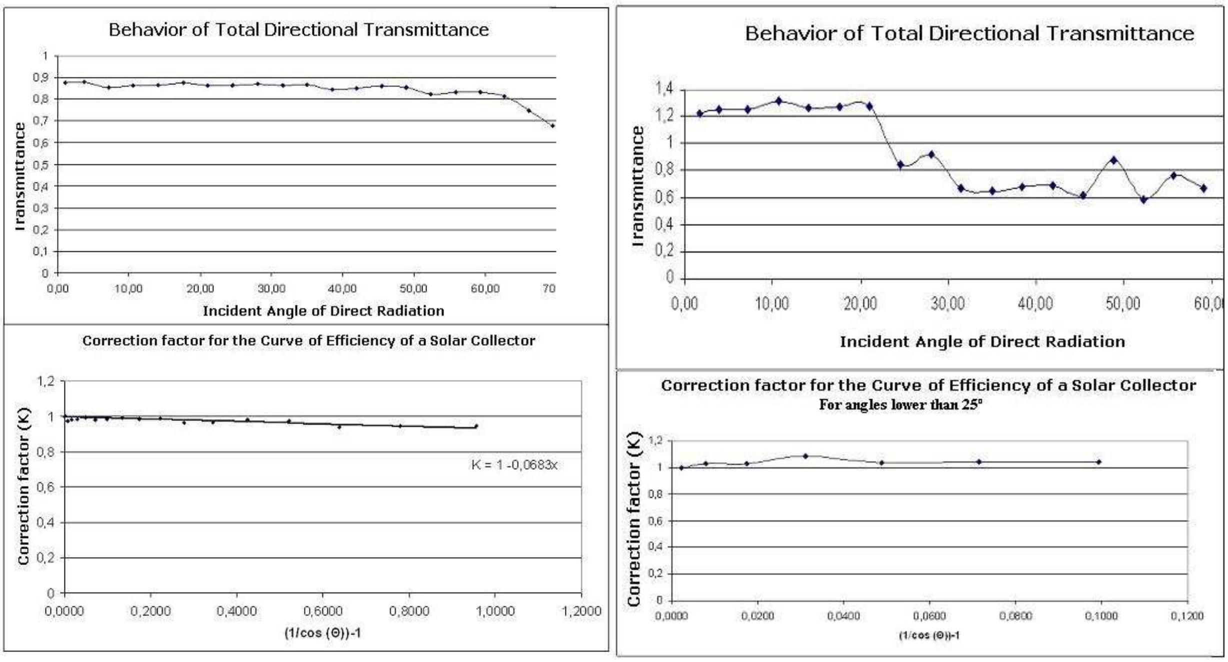
4.1. Outdoor Results



(a) (b)

Figure 7. (a) Sample 1 (b) Sample 2.

Figures 7 (a) and (b) represents the behavior of total directional transmittance of Style and Mini-Boreal glasses. It could be noted that Mini Boreal glass had a marked declined of his transmittance for incident angles after 30° and Style glass has a decline of his transmittance for incident angles after nearly 50°. These facts are important to know cause depending of the orientation and tilt of a solar collector it could be happen a great decrease of effectiveness work period of solar collector due to the lower transmittance of the glass.



(a) (b)

Figure 8. (a) Sample 3 (b) Sample 4 (angles <25º).

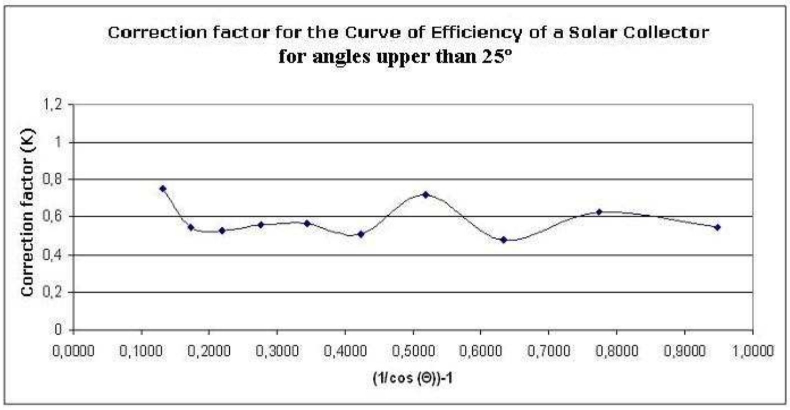
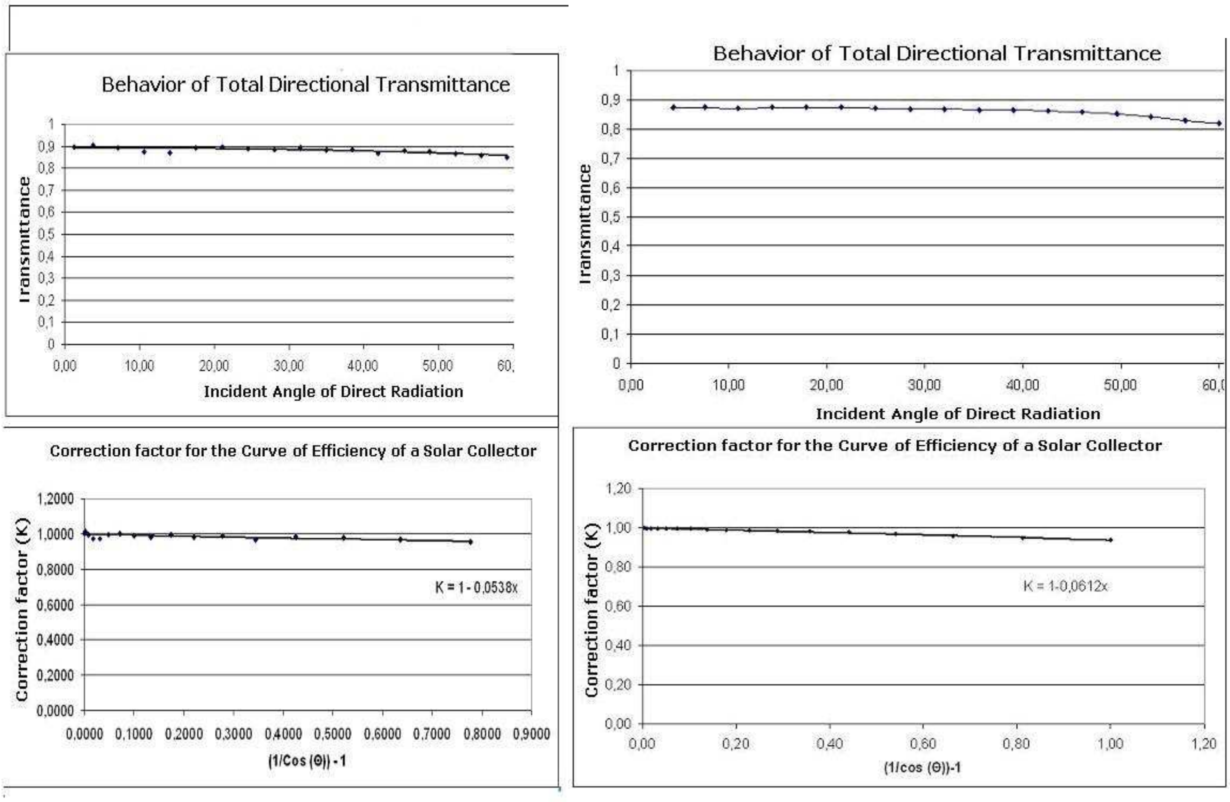


Figure 9. Sample 4 (angles >25º).

Figures 8 (a) and (b) and figure 9 also presents the behavior of total directional transmittance of Mini-Boreal Chinês and Pirâmide glasses respectively. It could be noted that Mini Boreal Chinês glass has of his transmittance for incident angles after 50° like Style glass but the pirâmide glass has a marked declined that starts at 20° and after that still going down. Like Style and Mini Boreal glasses, already discurssed, these decrease of transmittance could cause lower effectiveness work period for a solar collector.



(a) (b)

Figure 10. (a) Sample 5 (b) Sample Float (Control).

According to the graphs presented above the sample glass number 5 obtained the best total directional transmittance for up to 60 ° angles showing an average transmittance of 88.33% and correction factor (k) equal to 0.054 (Figure 10 (a)). The values for this glass were better than those reported for glass Float / control (mean: 86.07% k = 0061). Table 1 shows the summarized the results of transmittance (average and maximum) for each sample:

Table 1. Values of average and maximum transmittances

Samples	Experimental Transmittance	
	Average	Maximum
Float (Controle)	86,07%	87,51%
Sample 5	88,33%	90,88%
Sample 3	85,73%	87,94%
Sample 2	80,35%	87,13%
Sample 1	78,93%	83,60%
Sample 4<25º	126,44%	132,05%
Sample 4>25º	72,37%	127,27%
Sample 4 (Total)	88,51%	132,05%

4.2.Results solar simulators / indoor tests

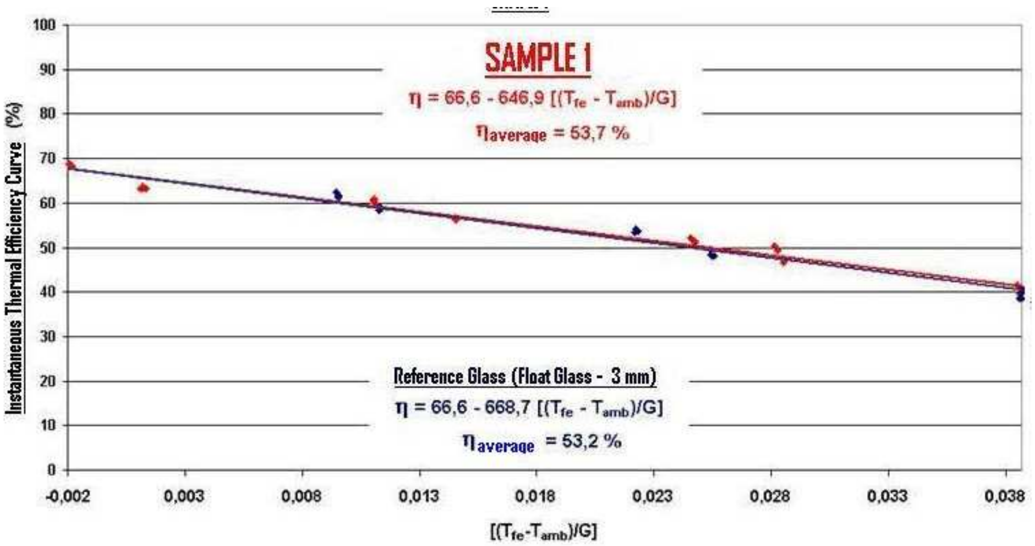


Figure 11. Instantaneous Thermal Efficiency Curve of Sample 1.

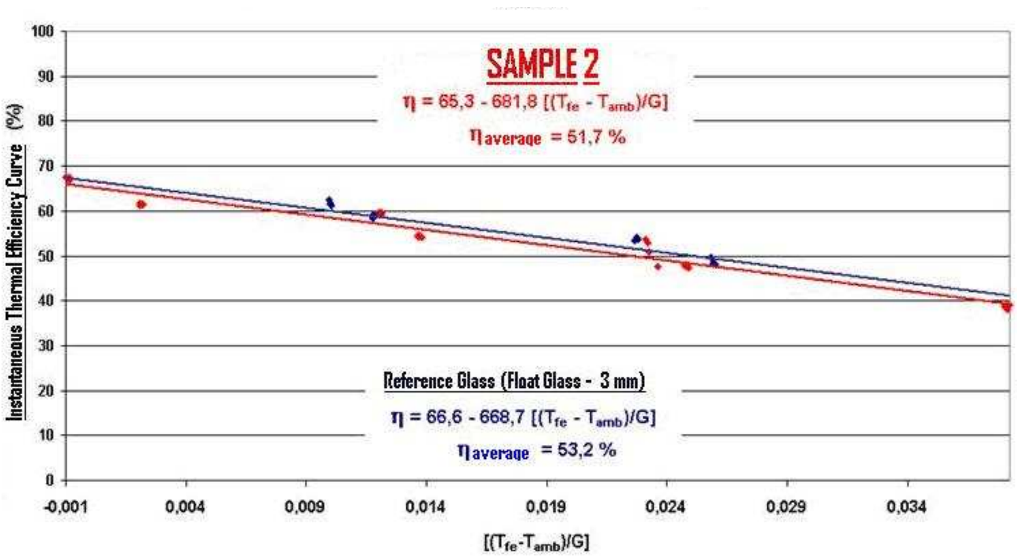


Figure 12. Instantaneous Thermal Efficiency Curve of Sample 2.

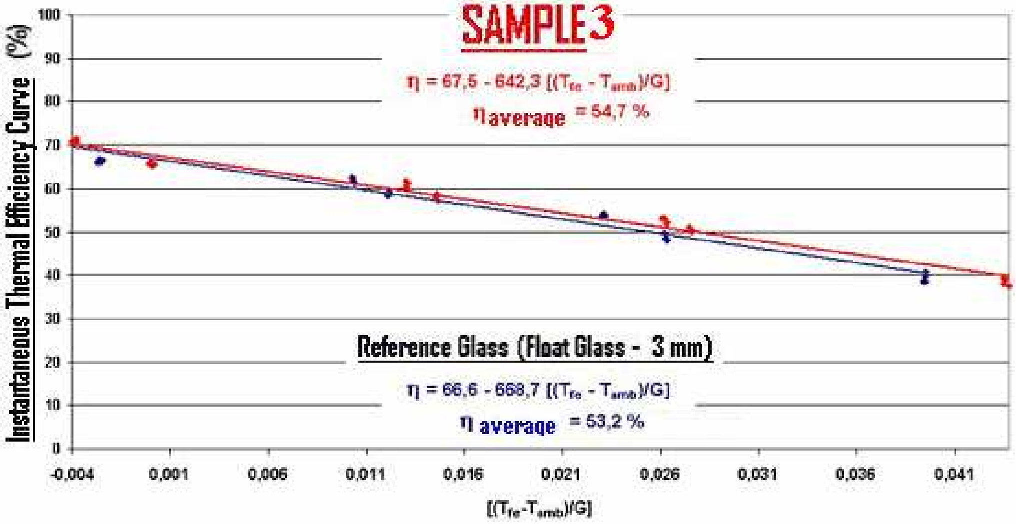


Figure 13. Instantaneous Thermal Efficiency Curve of Sample 3.

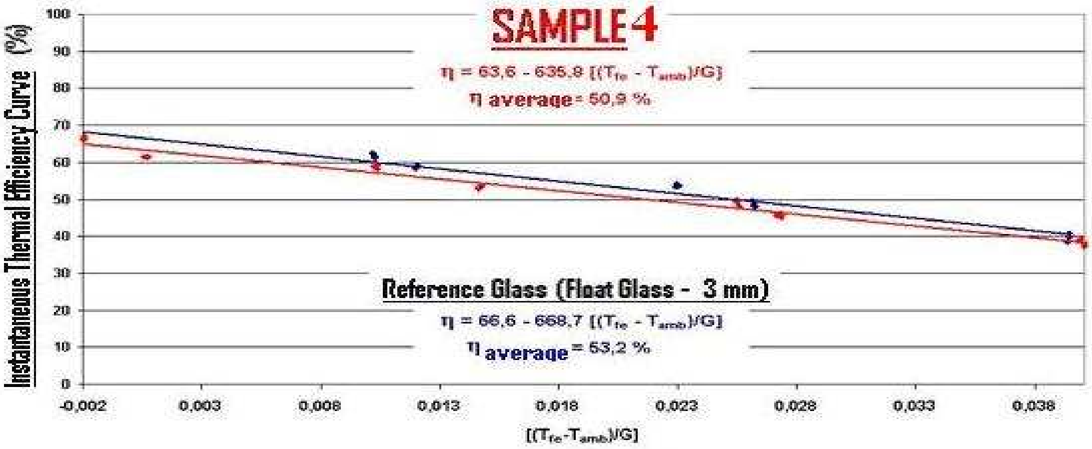


Figure 14. Instantaneous Thermal Efficiency Curve of Sample 4.

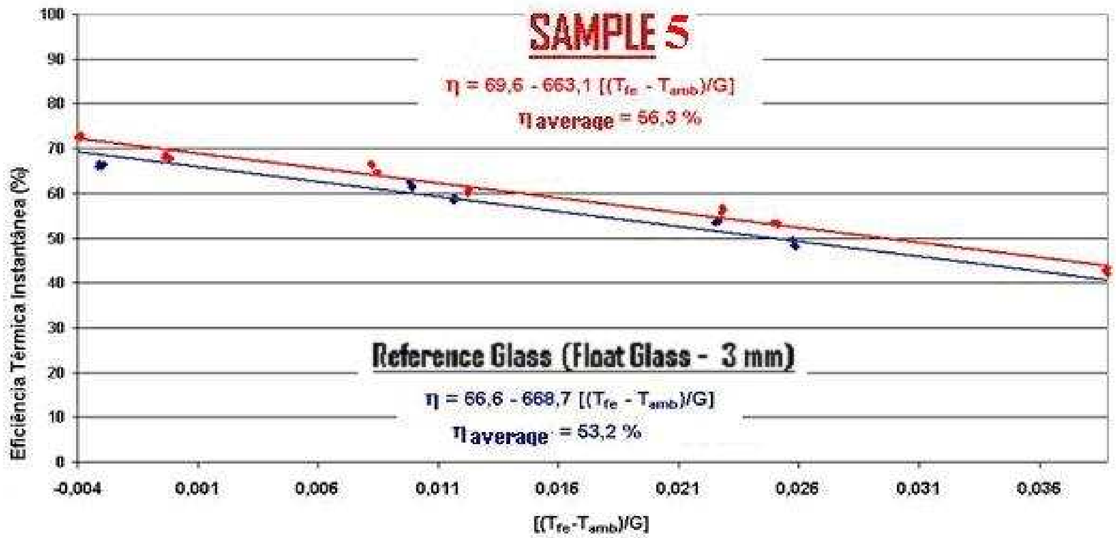


Figure 15. Instantaneous Thermal Efficiency Curve of Sample 5.

According to the graphs above the sample 5 was present, among samples tested, the best average efficiency η = 56.3% (figure 15),it should be noted that uncertainty evaluated of average efficiency test was approximately ± 1.5%, in relation with float glass normally used in solar collectors. Its production of energy was equivalent to 78.8 (kWh / month) which would be assigned the classification "A" second PBE / INMETRO. Table 2 shows the thermal efficiency, power generation and classification PBE for samples that were tested in the solar simulator.

Table 2. Thermal efficiency, power generation and classification PBE for different samples tested.

Samples	Data Evaluation Thermal Efficiency					Data Evaluation Especific Energy Production(Month)					
	Thermal Efficiency Curve		Axis X	Average	Standard Deviation	Parameters		PEME (kWh/ mês/m²)	PME (kWh/ mês)	Classif. PBE	Standard Deviation
	a	b	BANHO			Área (m²)	k'	BANHO			
Sample 5	69,6	663,1	0,020	56,3	5,85	1,00	0,0538	78,8	78,8	A	4,65
Sample 3	67,5	642,3	0,020	54,7	2,68	1,00	0,0683	76,1	76,1	B	1,06
Sample 2	66,6	646,9	0,020	53,7	0,82	1,00	0,1557	72,4	72,4	B	-3,85
Sample Float	66,6	668,7	0,020	53,2	Ref.	1,00	0,0612	75,3	75,3	B	Ref.
Sample 1	65,3	681,8	0,020	51,7	-2,93	1,00	0,2859	66,2	66,2	C	-12,08
Sample 4	63,6	635,8	0,020	50,9	-4,40	1,00	x	x	x	x	x

5.CONCLUSIONS

Were presented the results of tests (outdoor) total directional transmittances (τ) and their correction factor (k) for six different samples of glass (Sample 1 - Style, Sample 2 - Mini Boreal , Sample 3 - Mini Boreal Chinês, Sample 4 - Pirâmide, Sample 5 - Anti-Reflexo, Sample Float). The glass that had the best average value of transmittance was the Sample 5 (88.33%) with correction factor (k) equal to 0,054. The same glass also presented the best results tests, made in the solar simulator (indoor tests), of thermal efficiency with average of η= 56.3%, when compared with other samples and Float Glass (sample control). This glass attached to the solar collector presented a production of energy from 78.8 (kWh / month) and would be classified as "A" ranking according with PBE / INMETRO. Thus depending of the orientation and tilt of a solar collector that use this glass sample could improve his effectiveness work period due to his good glass transmittance.

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